

Measurement of the linear thermo-optical coefficient of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ using photonic crystal nanocavities

Sergei Sokolov,^{1,2, a)} Jin Lian,¹ Sylvain Combrié,³ Alfredo De Rossi,³ and Allard P. Mosk¹

¹⁾*Nanophotonics, Debye Institute for Nanomaterials Science, Center for Extreme Matter and Emergent Phenomena, Utrecht University, P.O. Box 80.000, 3508 TA Utrecht, The Netherlands*

²⁾*Complex Photonic Systems (COPS), MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*

³⁾*Thales Research & Technology, Route Départementale 128, 91767 Palaiseau, France*

(Dated: 19 December 2016)

$\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ is a promising candidate for thermally tunable nanophotonic devices due to its low thermal conductivity. In this work we study its thermo-optical response. We obtain the linear thermo-optical coefficient dn/dT by investigating the transmission properties of a single mode-gap photonic crystal nanocavity.

^{a)}s.a.sokolov@uu.nl; <http://www.nanolinx.nl/>

I. INTRODUCTION

Several III-V semiconductors are used for nanophotonic devices, such as GaAs¹, GaP², InP³ for their specific properties such as optical tunability. Local tuning of the refractive index has been proposed as a method to create localized resonances in a waveguide⁴, and to tune complex localized states^{5,6}. For local thermal tuning, the high thermal conductivity of Si or Si₃N₄ is unfavorable. A promising candidate for thermally tunable nanophotonic devices is GaInP which became popular during recent years^{7–11}. Its thermal conductivity¹² is more than 6 times smaller than for Si and Si₃N₄, which in addition to absence of two-photon absorption at 1550 nm and favorable nonlinear properties¹⁰ makes it a promising candidate for thermally tunable photonics. In this work we investigate the thermal response of a single photonic crystal nanocavity made of Ga_{0.51}In_{0.49}P. Our analysis allows us to obtain the thermo-optic coefficient of refractive index for this material whose precise value has not been reported in the literature to our knowledge.

II. SAMPLE AND EXPERIMENTAL SETUP

To experimentally measure the thermo-optical coefficient of the Ga_{0.51}In_{0.49}P a nanophotonic sample containing photonic crystal nanocavities was mounted on a thermally controlled stage, so the sample was homogeneously heated and the temperature was locked with a precision of ± 0.001 K. In a separate non-thermal run the sample itself was replaced by a PT-100 sensor, its temperature was never different from the base temperature by more than 2.1 K. The temperatures reported further are referred to this sample position. The sample is an air-suspended photonic crystal membrane with a linear array of 10 directly coupled mode-gap photonic crystal nanocavities made of Ga_{0.51}In_{0.49}P. The thickness of semiconductor membrane is 180 nm.

The structure of a single cavity is presented as the inset in Figure 1. It is made in a photonic crystal waveguide with $W_0 = 0.98\sqrt{3}a$ where $a=485$ nm is a period of a triangular photonic crystal lattice. Red holes are shifted away from the waveguide by 6 nm, green - by 4 nm and purple ones are shifted by 2 nm to create a cavity mode. Such cavities are known for large experimentally measured Q-factors^{13,14} and therefore they are suitable for precise thermal measurements. The first and last cavities in the array are coupled to input and output photonic crystal waveguides with width $W_1 = 1.1\sqrt{3}a$ which are used to launch and collect light from the structure. The structure was probed by IR light

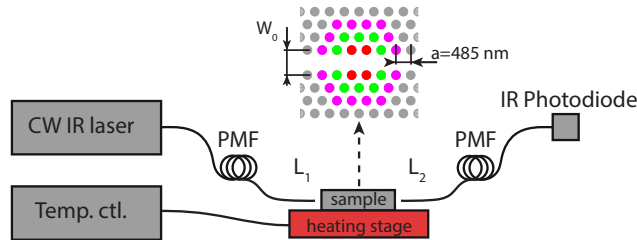


FIG. 1. **Experimental setup.** Transmission through the sample is measured. The sample temperature is locked to ± 0.001 °C using a temperature controller. Inset shows the cavity structure. Holes are represented with circles. Different colors correspond to different hole shifts.

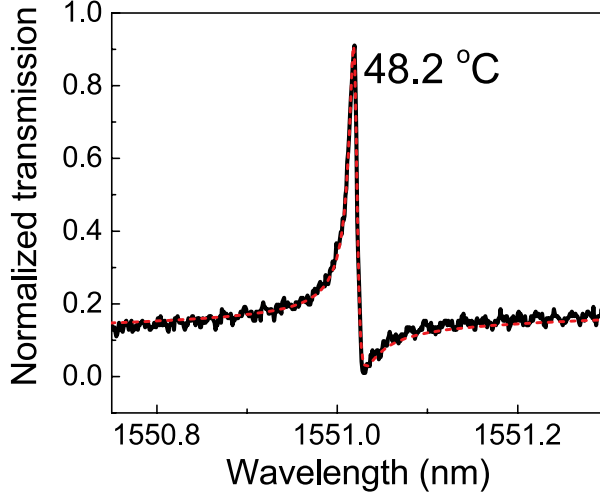


FIG. 2. **Transmission spectrum.** Transmission spectra of the sample at 48.2 °C. Dashed line represents Fano lineshape fit.

with a wavelength around 1550 nm from the CW tunable laser. The light was coupled into and out-coupled from the structure with polarization-maintaining lensed fibers L_1 and L_2 with NA=0.55. The out-coupled light was collected on an IR photodiode for transmission measurements. The sample was kept in nitrogen atmosphere to avoid oxidation^{15,16}. The resonance frequencies of cavities are perturbed by unavoidable disorder, which breaks the resonance hybridization. This normally undesired effect allowed us to pick an isolated single cavity resonance. We picked the single resonance corresponding to the 3rd cavity in the array, which was verified by our pump line-scan technique^{7,8,17}. The transmission spectrum of the resonance at 48.2 °C is presented in Figure 2. The spectrum has a clear Fano-like shape due to the interference with transmitted TM light. The spectrum is fitted with a Fano lineshape function^{18,19} with 1st order polynomial for the background. The lineshape is perfectly described by the fit, so it is used to obtain line parameters. The loaded Q-factor of the resonance is $Q = 1.6 \pm 0.1 \cdot 10^5$.

III. EXPERIMENT DESCRIPTION

For the measurement of the thermo-optical coefficient the resonance wavelength was measured for several temperatures of the sample ranging from 26 to 76 °C. Spectra for all temperatures are presented in Figure 3. The resonance experiences a redshift which signifies that the material has a positive thermo-optical response. All spectra have a Fano-like line shape. There was no systematic change of the Q-factor which signifies that within this temperature range the mode-profile of the cavity does not change. In total the resonance redshifts by about 4.5 nm when the temperature rises by approximately 49.5 °C. The dependence of resonance wavelength on the temperature of the sample is presented in Figure 4. The resonance wavelength changes linearly with increasing temperature, with a tuning slope of $9.4 \pm 0.2 \cdot 10^{-2}$ nm/K.

When a sample is heated, any water film is evaporated from the surface which causes a resonance blueshift¹⁵. The exact magnitude of this resonance shift depends on details of the surface condition. In laser heating experiments with similar temperature changes we

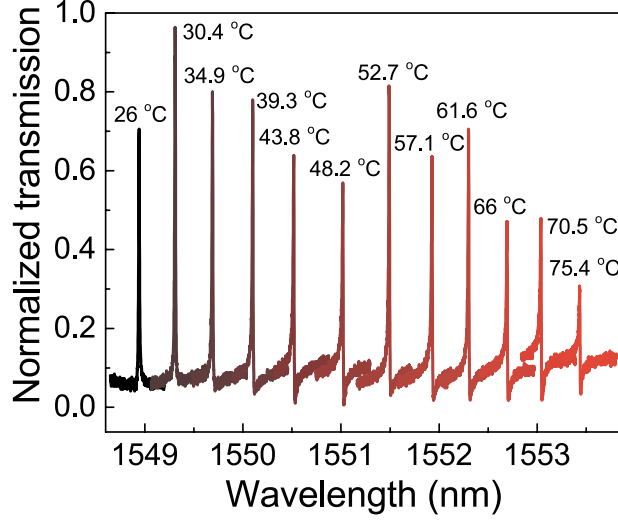


FIG. 3. **Transmission spectra.** Patched graph showing all transmission spectra collected in this experiment. Color of lines changes from black to red to emphasize the temperature difference.

have observed this shift to be 360 pm or less. To account for this a priori unknown shift we add an error term of 5%, resulting in $dn/dT = 9.4 \pm 0.5 \cdot 10^{-2} \text{ nm/K}$. Using first order

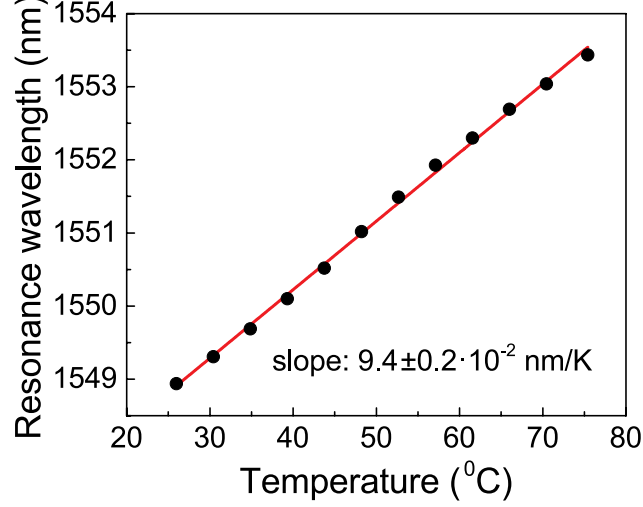


FIG. 4. **Resonance wavelength versus temperature of the sample.** The red line represents a line fit of the experimental data. The error for experimental data is smaller than the datapoint size.

perturbation theory and scaling of Maxwell equations one can get a precise value of linear thermo-optic coefficient dn/dT of the refractive index of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. To first order, it can be shown that²⁰:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\lambda_n}{\lambda} + \frac{\Delta\lambda_a}{\lambda} \quad (1)$$

Where $\Delta\lambda_n/\lambda$ and $\Delta\lambda_a/\lambda$ are equal to :

$$\frac{\Delta\lambda_n}{\lambda} = \frac{\Delta n}{n} \cdot \frac{\int_{\text{membrane}} \varepsilon |\mathbf{E}(\mathbf{r})|^2 d\mathbf{r}}{\int_{\text{all}} \varepsilon |\mathbf{E}(\mathbf{r})|^2 d\mathbf{r}} = \frac{1}{n} \frac{dn}{dT} \Delta T \mathcal{E}_m \quad (2)$$

$$\frac{\Delta\lambda_a}{\lambda} = \frac{\Delta a}{a} = \alpha_T \Delta T \quad (3)$$

Here $\Delta\lambda_n/\lambda$ is the relative resonance wavelength change caused by the refractive index change Δn , ε is the dielectric constant of the membrane material and $\mathbf{E}(\mathbf{r})$ is the electric field of the cavity mode. As follows from Eq. 2 the change of the resonance wavelength is proportional to the fraction of the electric-field energy inside the membrane \mathcal{E}_m , taking into account that the change in the refractive index of ambient nitrogen is negligible. According to our 3D FDTD calculations the fraction of electric-field energy in the membrane is 0.88. $\Delta\lambda_a/\lambda$ is the relative wavelength change due to the thermal expansion of the membrane, where α_T is the thermal expansion coefficient. The dn/dT value can be finally obtained from:

$$\frac{dn}{dT} = \frac{n}{\lambda \mathcal{E}_m} \left(\frac{d\lambda}{dT} - \alpha_T \lambda \right) \quad (4)$$

The thermal expansion coefficient²¹ α_T for $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ is equal to $5.4 \pm 0.3 \cdot 10^{-6} \text{ K}^{-1}$. The experimentally measured value of dn/dT is then equal to $dn/dT = 2.0 \pm 0.1 \cdot 10^{-4} \text{ K}^{-1}$. We note that in case of GaInP linear expansion gives a noticeable contribution to the tuning slope of the cavity resonance. Without taking into account that effect the value of dn/dT would be about 10% larger.

The value for dn/dT is about 30% smaller than the value obtained earlier⁷. The previous value was obtained as a result of comparison between complex modeling and experiment. We surmise that uncertainty of thermal conductivity of materials as well as laser power estimation in the focus may have led to overestimation of the result. Moreover, in this paper the sample was heated homogeneously so $(\frac{dn}{dT})_P$ was measured, while for the experiment with local laser heating, described in Ref.⁷, $(\frac{dn}{dT})_V$ was measured, which is actually a value for a stressed material as the membrane could not expand. The present experiment does not depend on laser pump power and thermal conductivity of the membrane material and therefore the obtained value of dn/dT corresponds to stress-free $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$.

IV. CONCLUSION

In conclusion, we investigated the thermo-optical effect of the refractive index for $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. Our measurement took place for a freely expanding membrane and we took into account the effect of thermal expansion of the material. We found no significant Q-factor change during our measurement which guarantees that the working wavelength of photonic devices based on nanocavities made of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ can be safely biased with temperature within the range of about 5 nm. This work enables precise thermal tuning of GaInP based photonic devices, which is relevant as one of the lowest thermal conductivity semiconductors used in photonics.

Funding. European Research Council project (ERC) (279248), Nederlandse Organisatie voor Wetenschappelijk.

Acknowledgement. The authors would like to thank Sanli Faez, Emre Yüce and Willem Vos for helpful discussions and advises and Cornelis Harteveld for technical support.

REFERENCES

- ¹A. Faraon, D. Englund, D. Bulla, B. Luther-Davies, B. J. Eggleton, N. Stoltz, P. Petroff, and J. Vučković, “Local tuning of photonic crystal cavities using chalcogenide glasses,” *Appl. Phys. Lett.* **92**, 043123 (2008).
- ²K. Rivoire, Z. Lin, F. Hatami, and J. Vučković, “Sum-frequency generation in doubly resonant GaP photonic crystal nanocavities,” *Appl. Phys. Lett.* **97**, 95–98 (2010).
- ³Y. Yu, E. Palushani, M. Heuck, N. Kuznetsova, P. Trøst, S. Ek, D. Vukovic, C. Peucheret, L. Katsuo, S. Combrié, A. D. Rossi, K. Yvind, and J. Mørk, “Switching characteristics of an InP photonic crystal nanocavity : Experiment and theory,” *Opt. Express* **21**, 9221–9231 (2013).
- ⁴M. Notomi and H. Taniyama, “On-demand ultrahigh-Q cavity formation and photon pinning via dynamic waveguide tuning,” *Opt. Express* **16**, 18657–18666 (2008).
- ⁵F. Riboli, N. Caselli, S. Vignolini, F. Intonti, K. Vynck, P. Barthelemy, A. Gerardino, L. Balet, L. Li, A. Fiore, M. Gurioli, and D. Wiersma, “Engineering of light confinement in strongly scattering disordered media,” *Nat. Mater.* **13**, 720 (2014).
- ⁶J. Pan, Y. Huo, K. Yamanaka, S. Sandhu, L. Scaccabarozzi, R. Timp, M. L. Povinelli, S. Fan, M. M. Fejer, and J. S. Harris, “Aligning microcavity resonances in silicon photonic-crystal slabs using laser-pumped thermal tuning,” *Appl. Phys. Lett.* **92**, 103114 (2008).
- ⁷S. Sokolov, J. Lian, E. Yüce, S. Combrié, G. Lehoucq, A. De Rossi, and A. P. Mosk, “Local thermal resonance control of GaInP photonic crystal membrane cavities using ambient gas cooling,” *Appl. Phys. Lett.* **106**, 171113 (2015).
- ⁸J. Lian, S. Sokolov, E. Yüce, S. Combrié, A. De Rossi, A. P. Mosk, and ., “Measurement of the profiles of disorder-induced localized resonances by local tuning,” *Opt. Express* **24**, 21939–21947 (2016).
- ⁹A. Martin, G. Moille, S. Combrié, G. Lehoucq, T. Debuisschert, J. Lian, S. Sokolov, A. P. Mosk, and A. De Rossi, “Triply-resonant Continuous Wave Parametric Source with a Microwatt Pump,” *arXiv:1602.04833 [physics.optics]* (2016).
- ¹⁰S. Combrié, Q. V. Tran, A. De Rossi, C. Husko, and P. Colman, “High quality GaInP nonlinear photonic crystals with minimized nonlinear absorption,” *Appl. Phys. Lett.* **95**, 221108 (2009).
- ¹¹A. S. Clark, C. Husko, M. J. Collins, G. Lehoucq, S. Xavier, A. D. De Rossi, S. Combrié, C. Xiong, and B. J. Eggleton, “Heralded single-photon source in a III-V photonic crystal,” *Opt. Lett.* **38**, 649–651 (2013).
- ¹²S. Adachi, “Lattice thermal conductivity of group-IV and III-V semiconductor alloys,” *J. Appl. Phys.* **102**, 063502 (2007).
- ¹³E. Kuramochi, M. Notomi, S. Mitsugi, A. Shinya, T. Tanabe, and T. Watanabe, “Ultrahigh-Q photonic crystal nanocavities realized by the local width modulation of a line defect,” *Appl. Phys. Lett.* **88**, 041112 (2006).
- ¹⁴S. Combrié, A. De Rossi, Q. V. Tran, and H. Benisty, “GaAs photonic crystal cavity with ultrahigh Q: microwatt nonlinearity at 1.55 microm.” *Opt. Lett.* **33**, 1908–1910 (2008).

- ¹⁵C. J. Chen, J. Zheng, T. Gu, J. F. McMillan, M. Yu, G. Lo, D. Kwong, and C. W. Wong, “Selective tuning of high-Q silicon photonic crystal nanocavities via laser-assisted local oxydation,” *Opt. Expr.* **19**, 12480 (2011).
- ¹⁶K. Navr, “Thermal oxidation of gallium arsenide,” *Czech. J. Phys. B* **18**, 266–274 (1968).
- ¹⁷S. Sokolov, J. Lian, E. Yüce, S. Combrié, A. De Rossi, and A. P. Mosk, “Canceling disorder-induced localization in nanophotonic cavity arrays,” arXiv:1608.01257 [physics.optics] (2016).
- ¹⁸U. Fano, “Effects of Configuration Interaction on Intensities and Phase Shifts,” *Phys. Rev.* **124**, 1866–1878 (1961).
- ¹⁹W. Zhou, D. Zhao, Y. C. Shuai, H. Yang, S. Chuwongin, A. Chadha, J. H. Seo, K. X. Wang, V. Liu, Z. Ma, and S. Fan, “Progress in 2D photonic crystal Fano resonance photonics,” *Prog. Quant. Electron.* **38**, 1–74 (2014).
- ²⁰J. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic Crystals: Molding the flow of light* (Princeton University Press, Princeton, 2008).
- ²¹I. Kudman and R. J. Paff, “Thermal expansion of $\text{In}_x\text{Ga}_{1-x}\text{P}$ alloys,” *J. Appl. Phys.* **43**, 3760–3762 (1972).